Preface

1 Introduction

The papers in this issue are by participants in a Workshop on *Time-symmetry in Quantum Mechanics,* which took place at the Centre for Time, University of Sydney, Australia in August, 2005.[1] In this Preface, we attempt to give some of the motivation for the subject of the Workshop and briefly mention a few highlights in the history of the subject.

2 Motivation

Reasons for examining time-symmetric formulations of physical theories generally and quantum mechanics in particular are discussed more fully in Price (1996). Here we mention just a few considerations. To remove any doubt, the Workshop was not concerned, at least directly, with the formal topic of time reversal invariance in quantum mechanics. The Workshop was motivated firstly by the puzzle of why the formalism of standard quantum mechanics is almost invariably dealt with in a time *asymmetric* way. While at least at first sight the Schrödinger equation may seem time-symmetric, the projection postulate is definitely time-asymmetric, so that to the list of puzzles that measurement brings into quantum mechanics one needs to add that of time-asymmetry.[2]

According to several workers in the field, the source of the problem may lie even deeper, in the use of the Schrödinger equation itself. Indeed, in the case of classical electromagnetism, the advanced solutions are discarded. In the case of standard (non-relativistic) quantum mechanics, two "Schrödinger" equations emerge as the non-relativistic limit of a relativistic treatment (see, for example, Cramer (1986)). One equation corresponds to evolution of the quantum state forwards in time and the other (its complex conjugate) corresponds to evolution backwards in time. Many of the discussions of time symmetry in quantum mechanics, including several (but by no means all) examples in the present issue, rely on some version of a 'two-vector' formalism, which explicitly includes both "Schrödinger" equations.

A further motivation for considering time-symmetric formulations of quantum mechanics is the possibility that they might throw light back onto the measurement problem and other interpretational issues, such as the EPR paradox and nonlocality. It is at this point that issues of time symmetry in quantum mechanics become explicitly related also to the exploration of backwards causation.

In the face of Bell's theorem, the usual approach is to accept either action at a distance or uncaused correlations via the concepts of "nonlocality" or "nonseparability" of quantum systems. As pointed out in Price (1996) and several of the papers in this issue, the alternative of using a time-symmetric theory with backwards causation has been very much neglected. If the effect of a measurement setting is allowed to propagate backwards in time from one measurement to the source (and forwards in time to the other measurement), the space-like correlations can in principle be easily explained using time-like causal processes.

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[1] Presentations at the Workshop were given by Guido Bacciagaluppi, Jossi Berkovitz, John Cramer, Avshalom Elitzur, Richard Healey, Dipankar Home, Noboru Hokkyo, Ruth Kastner, Tony Leggett, David Miller, David Pegg, Huw Price, Larry Schulman, Michael Silberstein, Rod Sutherland, Roderich Tumulka, Jos Uffink and Lev Vaidman. Other participants at the Workshop included Howard Barnum, Stephen Bartlett, Michael Cifone, John Corbett, John Cusbert, Paul Davies, Jennifer Dodd, Thomas Durt, Shelly Goldstein, Jason Grossman, Roy Hughes, Peter Lewis, Gerard Milburn, Wayne Myrvold, Michael Nielsen, Andrew Norton, David Poulin, Kenny Pregnell, Terry Rudolph, Jason Semitecolos, Nick Smith, Mark Stuckey, Jeff Tollaksen, Frank Valkenborgh, Brad Weslake and Howard Wiseman.

[2] One needs to distinguish further whether the postulate is taken to be part of the theory in some form (collapse theories) or only effective (no-collapse theories). In the latter case, much more work is needed on the relation between time symmetry and decoherence (for some of the issues involved, see Bacciagaluppi (2007)).

Besides nonlocality, some time-symmetric approaches may provide an intuitive explanation of contextuality; for example the probabilities in Aharonov and Vaidman's (2002) two-vector formalism are contextual (as, by Gleason's theorem, must any probabilities that are not defined as usual by a single vector or density matrix); see also Miller (1998).

3 History

There are many references to the desirability of time-symmetric formulations of physical theories. Hokkyo (1988) refers to some of the literature. Here we mention only some of the main contributions which are concerned directly or indirectly with non-relativistic quantum mechanics. Perhaps the first significant step was made in the 1940s, when Richard Feynman began a research program initially concerned with classical electromagnetism but later applied to quantum mechanics and quantum field theory. The program relied on four assumptions (Schweber, 1994, p. 383), of which the third was this: *The fundamental (microscopic) phenomena in nature are symmetrical with respect to interchange of past and future.* This assumption led Feynman, in joint work with Wheeler, to a theory of electromagnetism in which the above assumption was satisfied by including advanced and retarded potentials with equal status (Wheeler and Feynman, 1945).

As Wheeler and Feynman note, the proposal to accord an equal status to the emission and absorption of radiation develops a suggestion due to Tetrode (1922), who had proposed, as Wheeler and Feynman put it (1945, p. 159), "to abandon the conception of electromagnetic radiation as an elementary process and to interpret it as a consequence of an interaction between a source and an absorber". A consequence of this suggestion, as Tetrode himself describes it, would be that "the sun would not radiate if it were alone in space and no other bodies could absorb its radiation'' (Tetrode 1922, p. 325). This is a striking early manifestation of the view that what happens in reality might depend crucially on conditions in the future, as well as in the past.

In his PhD thesis in 1942, Feynman had already noted that the same kind of reasoning has consequences for quantum mechanics : "… the spontaneous radiation of an atom in quantum mechanics also, may not be spontaneous at all, but induced by the interaction with other atoms, …" (Feynman, 1942, p. 4), and this led him ultimately to the path integral formulation. The half-advanced and half-retarded potentials do not appear in the final expression for the action in the path integral formulation (Feynman, 1965) but conceptually the theory still depends on "the amplitude that the source will emit and *the detector receive"* (Feynman, 1965, p. 167, emphasis added). One consequence is that, because radiation must be received by other atoms, "an atom alone in empty space would, in fact, *not* radiate" (Feynman, 1942, p. 4, emphasis in the original).

There have been several attempts over the years to elaborate on the advanced-action aspect of the path integral formulation. In the current volume, Hokkyo considers the two-slit experiment from that point of view and suggests there may be an experimental test.

At about the same time (see footnote 1 in Price's paper in this issue) as Feynman's program was underway, Costa de Beauregard (1953, 1977, 1979) had already proposed a time-symmetric, retrocausal view of quantum mechanics, to address what is now known as nonlocality.

In 1964, Aharonov, Bergmann and Lebowitz (ABL) noted that the quantum theory of measurement introduced an apparent time-asymmetry in quantum mechanics at a fundamental level. They proposed that this was due a bias introduced because quantum mechanics was concerned with calculating probabilities for ensembles of quantum systems "pre-selected" by the preparation procedure. They considered ensembles which were also post-selected, by the outcome of a final measurement in a sequence of measurements and showed that, at the microscopic level, "in time-symmetrically constructed ensembles the laws of probability are also time-symmetric" (Aharonov *et al*., 1964, p. B1416). The ABL formalism led to the two-vector re-formulation of quantum mechanics (Aharonov and Vaidman, 2002; Aharonov and Tollaksen, 2007), also referred to as time-symmetric quantum mechanics (TSQM). TSQM is open to conflicting interpretations. On one reading of the formalism, the "two-vectors" are the preparation state evolved forward in time and the state selected by a later measurement evolved backwards in time. Seen in this light, TSQM makes the same testable predictions as quantum mechanics and its major advantage is in providing a different point of view which stimulates new ideas or solutions to old problems. On another level, it has been suggested for instance that TSQM allows unmeasured properties to be ascribed to a quantum system between measurements, in which case it leads to a different ontology from standard quantum mechanics. Whether or not that step is justified has been a matter of discussion in the literature and the contribution by Ruth Kastner in the present volume touches on that issue. If TSQM is taken to have ontological significance, it represents an advanced-action theory (for the most recent comments on its ontological status, see Aharonov *et al*. (2007)) which provides a specific expression for how the hidden variables are partly determined by the next measurement as well as the preparation. The problem of nonlocality over spacelike intervals is dealt with by the backwards evolution, over a guaranteed timelike path, of a subsequent measurement state. As noted above, if the TSQM formalism is also applicable as a type of hidden variable theory, then the contextuality requirement is accommodated automatically in TSQM.

The transactional interpretation of quantum mechanics proposed by John Cramer (1986) in the 1980s was another major step in the application of the "advanced action" concept in quantum mechanics. The "transaction" is based on the exchange of retarded and advanced waves which are the solutions, respectively, of the Schrödinger equation and its complex conjugate (which both result from the taking the non-relativistic limit of the Dirac eqution). The emitter-absorber transaction provides a specific explanation of nonlocality and the transactional interpretation expressly proposes a different ontology from standard quantum mechanics. In the current volume, Ruth Kastner deals with the transactional interpretation in relation to the concept of "weak values" in TSQM. Tim Maudlin (1994) has suggested that the transactional interpretation is inconsistent. In the current volume, Jossi Berkovitz discusses this problem in terms of the causal loops which are involved.

The above few examples show that concept of advanced action or backward causation is of interest from the foundations point of view and as a stimulant of new ideas. It is also useful from a practical point of view. Over many years David Pegg has applied the ideas of post-selection in quantum engineering applications as well as investigating these ideas from a fundamental viewpoint. In the current volume he briefly reviews the relevant formalism and applies the ideas to some well-known quantum paradoxes.

4 Problems and outlook

There are several general problems which an advanced-action formulation of quantum mechanics must deal with. First, it might be wondered whether it is sensible to propose an advanced-action theory when nature appears to exhibit several "arrows of time" specifying a preferred direction of time evolution and causality. In the present volume, Larry Schulman discusses the thermodynamic and cosmological arrows of time in relation to retrocausality. Apart from dealing with the arrows, he also refers to his earlier proposal that the "grotesque" states (superpositions of macroscopic objects predicted by standard quantum mechanics without the arbitrary collapse postulate) can be avoided by special initial states. He suggests that these "special states" may be the result of boundary conditions in which "there is a substantial lack of entanglement among large objects". A similar condition is relied on by

David Miller in his contribution to the present volume where it is proposed that measurement outcomes in the laboratory are ultimately determined by initial and final boundary conditions on a cosmological time scale, rather than directly by the properties of the measured quantum system which are then said to be determined by the preparation and measurement themselves.

Another problem concerns the possibility of closed causal loops. The contribution in the current volume by Jossi Berkovitz provides a very thorough discussion of the types of both deterministic and indeterministic loops which might arise in such models, and whether or not they are inconsistent and therefore pose a problem to advanced-action theories. David Pegg's contribution shows how closed causal loops can be investigated in the laboratory.

Finally, there remain conceptual and technical challenges associated with the project of implementing these ideas in realistic models. The contributions in this volume make progress with these challenges, but much remains to be done. We trust that these papers will provide a stimulus to further research.

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References

Aharonov, Y., Bergmann, P. G., & Lebowitz, J. L. (1964). Time symmetry in the quantum process of measurement, *Physical Review*, **134**, B1410-B1416.

Aharonov, Y., Popescu, S., Tollaksen, J. & Vaidman, L. (2007). Multiple-time states and multiple-time measurements in quantum mechanics. (arXiv:0712.0320v1 [quant-ph])

Aharonov, Y., & Tollaksen, J. (2007). New insights time-symmetry in quantum mechanics. To appear in R. Y. Chiao, M. L. Cohen, A. J. Leggett, W. D. Phillips, and C. L. Harper, Jr. (Eds.), *Visions of discovery: new light on physics, cosmology, and consciousness*. Cambridge: Cambridge University Press. (arXiv:0706.1232v1 [quant-ph])

Aharonov, Y., & Vaidman, L. (2002). The two-state vector formalism of quantum mechanics. In J. G. Muga, R. Sala Mayato and I. L. Egusquiza (Eds.), *Time in quantum mechanics* (pp. 369-412). Berlin: Springer-Verlag. (arXiv:quant-ph/0105101v2)

Bacciagaluppi, G. (2007). 'Probability, arrow of time and decoherence', *Studies in History and Philosophy of Modern Physics,* **38**, 439-456.

Costa de Beauregard, O. (1953). 'Une réponse à l'argument dirigé par Einstein,Podolsky et Rosen contre l'interprétation Bohrienne des phénomènes quantiques'. *Comptes Rendus de l'Académie des Sciences*, **236**, 1632-1634.

Costa de Beauregard, O. (1977). Time symmetry and the Einstein paradox. *Il Nuovo Cimento B,* **42**, 41-64.

Costa de Beauregard, O. (1979). Time symmetry and the Einstein paradox 2. *Il Nuovo Cimento B,* **51**, 267-279.

Cramer, J. G. (1986). The transactional interpretation of quantum mechanics. *Reviews of Modern Physics*, **57**, 647-688.

Feynman, R. P. (1942). The principle of least action in quantum mechanics. In L. M. Brown (Ed.), *Feynman's thesis: a new approach to quantum theory.* Singapore: World Scientific.

Feynman, R. P. (1965). The development of the space-time view of quantum electrodynamics. In G. Ekspong (Ed.) *Physics: Nobel Lectures*. Singapore: World Scientific (1988).

Hokkyo, N. (1988). Variational formulation of transactional and related interpretations of quantum mechanics. *Foundations of Physics Letters*, **1**, 293-299.

Maudlin, T. (1994). *Quantum non-locality and relativity*. Oxford: Blackwell.

Miller, D. J. (1998). A contextual probability measure for real properties of quantum systems. In S. C. Lim, R. Abd-Shukor and K. H. Kwek (Eds.), *Frontiers in quantum physics* (pp. 224-228). Singapore: Springer-Verlag Singapore.
Price, H. (1996). *Time's arrow and Archimedes' point: new directions for the physics of time.* Oxford: Oxford University Press.
Schweber, S. S. (1994). *QED and the men who made it*. Princeton: Princeton University Press.
Tetrode, H. (1922). Über den Wirkungszusammenhang der Welt. Eine Erweiterung der klassischen Dynamik. *Zeitschrift für Physik,* **10**, 317-328.
Wheeler, J. A., & Feynman, R. L. (1945). *Reviews of Modern Physics,* **17**, 157-181.

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